Simulation Evaluation of a Speed-Guidance Law for Harrier Approach Transitions

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SYMBOLS

d	aircraft range from the selected station-keeping point, ft
d_r	range at which the aircraft should be reconfigured, ft
d_p	range at which the pilot is alerted to reconfigure the aircraft, ft
D_f	threshold range, ft
f_{ae}	length of the speed guidance ribbon, deg
g	acceleration due to gravity, ft/sec^2
K_{ax}	acceleration error gain, deg sec^2/ft
K_{θ_j}	factor used to correct $\bar{X}_u$, 1/sec
s	Laplace transform variable, 1/sec
v_a	airspeed, ft/sec
v_a^n	airspeed, knots
v_x	horizontal longitudinal speed relative to the station-keeping point, ft/sec
v_x^n	horizontal longitudinal speed relative to the station-keeping point, knots
$\dot{v}_x$	horizontal longitudinal acceleration, ft/sec^2
$\dot{v}_{xr}$	reference value of $\dot{v}_x$, ft/sec^2
V_{xf}	desired value of v_x at the threshold ($d = D_f$), ft/sec
V_w	wind speed, ft/sec
V_w^n	wind speed, knots
V_w'	effective wind speed, ft/sec
X_u	longitudinal force derivative, 1/sec
$\bar{X}_u$	sign reversed slope of range versus speed line, 1/sec
$\bar{X}_u'$	factor used to correct $\bar{X}_u$, 1/ft
$\bar{X}_{u_0}$	sign reversed slope of range versus groundspeed line for no wind and $\theta_n + \Theta_{jf} = 90°$, 1/sec
Δh	vertical deviation from the glidepath, ft
ΔT	pilot-alert lead time, sec
ΔV	final-longitudinal-velocity bias, ft/sec
β	sideslip angle, deg
β_c	commanded sideslip angle, deg
δ_t	throttle angle, deg
γ	flightpath angle, deg
θ	pitch angle, deg
θ_c	commanded pitch angle, deg
$\dot{\theta}$	pitch rate, deg/sec
$\dot{\theta}_c$	commanded pitch rate, deg/sec
θ_n	nominal pitch angle on the approach, deg
θ_j	engine nozzle angle, deg
$\dot{\Theta}_j$	engine nozzle-angle rate, deg
Θ_{jf}	final engine-nozzle angle after approach reconfiguration, deg
$\dot{\phi}$	roll rate, deg/sec
$\dot{\phi}_c$	commanded roll rate, deg/sec

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| $\dot{\psi}$ | yaw rate, deg |
| $\dot{\psi}_c$ | commanded yaw rate, deg/sec |

ACRONYMS

AC	Attitude command
ARINC	Aeronautical Radio Incorporated
HQR	Handling qualities rating
HUD	Head-up display
IFR	Instrument flight rules
MDC	McDonnell Douglas Corporation
RCAH	Rate command, attitude hold
RCS	Reaction control system
RVR	Runway visual range
SAS	Stability Augmentation System
SCT	Systems Control Technology, Inc.
STOL	Short Take-Off and Landing
V/STOL	Vertical and short takeoff and landing
VTOL	Vertical takeoff and landing

SUMMARY

An exponential-deceleration speed guidance law is formulated which mimics the technique currently used by Harrier pilots to perform decelerating approaches to a hover. This guidance law has been tested along with an existing two-step constant-deceleration speed guidance law, using a fixed-base piloted simulator programmed to represent a YAV-8B Harrier. Decelerating approaches to a hover at a predetermined station-keeping point were performed along a straight (−3° glideslope) path in headwinds up to 40 knots and turbulence up to 6 ft/sec. Visibility was fixed at one-quarter n. mi. and 100-ft cloud ceiling. Three Harrier pilots participated in the experiment.

Handling qualities with the aircraft equipped with the standard YAV-8B rate damped attitude stability augmentation system were adequate (level 2) using either speed guidance law. However, the exponential-deceleration speed guidance law was rated superior to the constant-deceleration speed guidance law by a Cooper-Harper Handling-Qualities Rating of about one unit independent of the level of wind and turbulence.

Replacing the attitude control system of the YAV-8B with a high fidelity model-following attitude flight-controller increased the approach accuracy and reduced the pilot workload. With one minor exception, the handling qualities for the approach were rated satisfactory (level 1).

It is concluded that the exponential-deceleration speed guidance law is the most cost effective.

INTRODUCTION

The standard, single-pilot visibility minima for landing Harrier vertical and short takeoff and landing (V/STOL) aircraft (AV-8C and AV-8B) at land based sites is one-half n. mi. runway visual range (RVR) and 200-ft cloud ceiling. Because of generally less accurate navigational aids, these minima are increased for landings aboard ships to 1 n. mi. RVR and 300 ft cloud ceiling. The established approach technique starts at a stabilized airspeed in the range of 110-130 knots, using an engine exhaust nozzle angle of 40-50°. At a range from the landing area of between 3000 ft and 6000 ft, the pilot reconfigures the propulsion system by changing the engine nozzle angle to the hover position. During the ensuing deceleration, the pilot continuously increases engine power to compensate for the decreasing aerodynamic lift, while using pitch attitude changes to modulate the deceleration so as to bring the aircraft to a hover at the desired station-keeping point. The specific point in the approach at which the engine nozzle is moved depends largely on the airspeed and wind speed and requires accurate pilot judgement. The decelerating part of the approach is performed below the cloud ceiling and is satisfactory if the visual cues are good. However, under some conditions, particularly at night, the cues are significantly degraded so that the deceleration is less precise and the aircraft is moving either too fast or too slow close to the station-keeping point (usually too slow). Overall operational

capability would be improved significantly if the current technique were aided by cockpit instruments. To mimic the current technique, lateral, vertical and speed guidance must be provided to the pilot, preferably on a head-up display (HUD). The speed guidance must indicate the pitch attitude changes needed to modulate the deceleration accurately. An additional refinement would be an indicator for the appropriate time to move the engine nozzle to the hover position.

A guidance scheme aimed at meeting the above requirements is given in reference 1. This scheme was designed to provide approach guidance down to hover and was tested using the X-22A to simulate the AV-8B Harrier II. A variety of attitude control laws and displays of varying complexity were tested and it was shown that for many control/display combinations, the guidance scheme permitted instrument approaches to hover. Unfortunately, because of flight envelope limitations of the X-22A, the approaches had to start at 65 knots, so that the more gust-critical airspeed range from 60 knots to 130 knots was not investigated. In addition, the data reported in reference 1 are sparse, making interpretation difficult.

This paper presents a speed guidance scheme that differs from that of reference 1 in both the algorithm used to indicate the range at which the nozzle should be moved to the hover position (reconfiguration range) and the speed guidance law itself. It is shown that the reconfiguration range is more accurate than that given in reference 1 and the guidance law uses a deceleration error based concept that promises reduced pilot workload. This scheme is aimed at bringing the aircraft to a predetermined speed at a predetermined range (termed the threshold) relative to the station-keeping point. Typical values for the final speed and threshold are 20 ft/sec and 200 ft, respectively. The task of finally acquiring the station-keeping point is carried out visually, if possible, or using the type of HUD presented terminal guidance scheme indicated in reference 2.

The speed-guidance law was simulated on a fixed-base piloted simulator. The baseline aircraft model used was that of a YAV-8B Harrier, and the HUD format used was that of reference 2. A variety of attitude control systems were used in the tests, ranging from the original YAV-8B rate-damped stability augmentation system (SAS) to full attitude command. The evaluation task was a decelerating approach to a hover at a preselected station-keeping point over a STOL runway, in various winds and turbulence. For comparison under identical circumstances, similar tests were performed using the two-step constant-deceleration speed guidance law described in reference 2.

The paper starts with a derivation of the reconfiguration range equation, along with a discussion of how it differs from that used in reference 1. An argument for an acceleration error, rather than a speed error (ref. 1), guidance concept is given and the exponential-deceleration speed guidance law is derived in a form that shows its close relationship to the constant-deceleration speed law of reference 2. The modifications to the HUD symbol drive laws (ref. 2) needed to implement the new guidance scheme are described. Then follows sections describing the control laws tested, the YAV-8B aircraft and the simulation details. Finally the results of the simulation are presented and discussed.

THE RECONFIGURATION RANGE

To improve precision and minimize the pitch attitude changes during the approach, it is desirable to alert the pilot when to reconfigure the aircraft for final approach. For maximum effectiveness, the pilot should reconfigure the aircraft within a few seconds of the optimum time. If, for some reason, the pilot delays the reconfiguration, the guidance law should indicate the need for increased deceleration. This additional deceleration may be achieved either by increasing the pitch angle or by increasing the engine nozzle angle beyond the selected value prior to the start of the deceleration.

The reconfiguration alert requirement can be met if a suitably accurate equation of motion can be obtained which describes the post-reconfiguration deceleration of the aircraft, allowing for winds and the preselected nozzle angle. An analytical approach to obtaining such an equation is infeasible because of the complexity of both the basic and propulsion induced aerodynamics. The much simpler approach adopted here was to perform a test using a piloted simulation of the YAV-8B Harrier. In this test the pitch angle was set to the nominal approach value (6.5°) and the power setting and engine nozzle angle set so that the aircraft was in the steady state and descending along a −3° glideslope at the highest airspeed possible prior to final reconfiguration (120 knots). The aircraft was then reconfigured and the speed and distance covered from the reconfiguration point to hover recorded. The test was performed in calm air conditions. The results of the test are shown in figure 1. Surprisingly, considering the complexity of the aerodynamics of this aircraft, the speed/distance relationship shown in figure 1 is almost linear and can be expressed sufficiently accurately by the equation

$$d = \frac{-v_x}{\bar{X}_u} \tag{1}$$

where

d range of the aircraft measured from the hover point, ft

v_x groundspeed, ft/sec

$\bar{X}_u$ sign reversed slope of the range versus groundspeed line, (may be regarded as an average of the stability derivative X_u), 1/sec

Equation (1) shows that, after reconfiguration, the aircraft's velocity decays exponentially with time. Without winds, equation (1) would suffice to determine the reconfiguration range, d_r, given v_x. However, allowance must be made for the effect of winds, since winds heavily influence the deceleration corresponding to a given groundspeed and, therefore, the reconfiguration range. To generalize equation (1) to include the effect of winds, it is necessary to first convert it to an equation of motion. This can be done by differentiating with respect to time, noting that $\delta d / \delta t = -v_x$, thus,
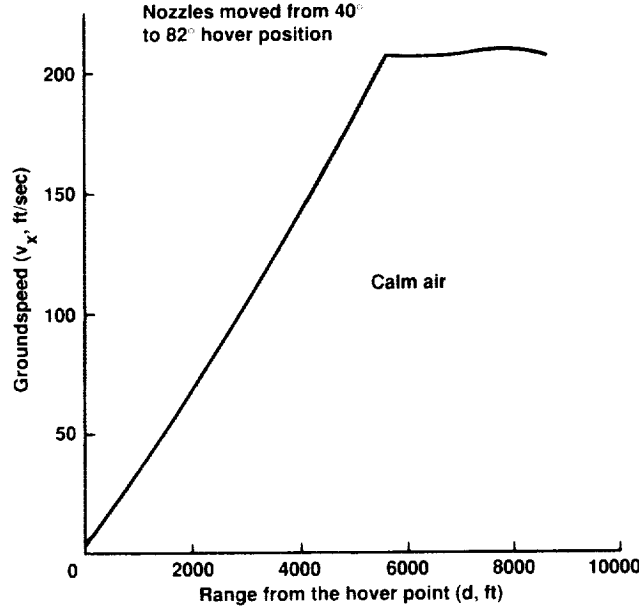
$$\dot{v}_x = \bar{X}_u v_x \tag{2}$$

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Figure 1. YAV-8B Harrier groundspeed vs. range characteristic after reconfiguration.

The deceleration of the aircraft is due to aerodynamic forces that are functions of the airspeed v_a. The groundspeed v_x appears in equation (2) only because in the test from which it was derived, groundspeed and airspeed were the same, i.e., no wind. It follows that equation (2) can be expressed in a more general form by replacing v_x by the airspeed, v_a. Since $v_a = v_x + V_w$, where V_w is a constant headwind speed, equation (2) becomes

$$\dot{v}_x = \bar{X}_u(v_x + V_w) \tag{3}$$

Equation (3) is satisfactory provided that the reconfigured aircraft has its gross thrust vector pointing vertically, as in the test from which it was derived. Any changes in engine nozzle or pitch angles causing the gross thrust vector to deviate from the vertical will invalidate equation (3). An acceptable correction to equation (3) to account for a non-vertical thrust vector is to add the acceleration per unit mass in hover. Although this correction is strictly valid only in hover, the error involved in assuming that it holds at all airspeeds on the approach is acceptable, because most of the time taken to complete the deceleration is at low speed. The resulting final equation of motion is

$$\dot{v}_x = g \cos(\theta_n + \Theta_{jf}) + \bar{X}_u(v_x + V_w) \tag{4}$$

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where

θ_n nominal pitch angle, deg

Θ_{jf} final nozzle angle with respect to the aircraft's longitudinal axis, deg
(for the Harrier, Θ_{jf} is the sum of the nozzle angle indicated in the
cockpit and a 1.5° inclination of the engine relative to the aircraft's
longitudinal axis)

g acceleration due to gravity, ft/sec^2

Note that when $\theta_n + \Theta_{jf} = 90°$, the gross thrust vector is vertical and the added term in equation (4) is zero.

Equation (4) can be written in the form

$$\dot{v}_x = \bar{X}_u \left[v_x + V_w + g\cos(\theta_n + \Theta_{jf})/\bar{X}_u \right]$$

or

$$\dot{v}_x = \bar{X}_u(v_x + V'_w) \tag{5}$$

where

$$V'_w = V_w + g\cos(\theta_n + \Theta_{jf})/\bar{X}_u \tag{6}$$

The quantity V'_w can be regarded as an effective wind speed taking into account the nominal approach pitch angle, θ_n, and approach nozzle angle, Θ_{jf}, selected prior to reconfiguration. Note that if $\theta_n + \Theta_{jf} = 90°$, then the effective wind is equal to the true wind. Assuming θ_n and Θ_{jf} are constant, equation (5) can be expressed in the following integral form, using the fact that $\dot{v}_x = -v_x \delta v_x / \delta d$,

$$\int_{V_{xf}}^{v_x} \frac{v_x}{v_x + V'_w} \delta v_x = - \int_{D_f}^{d} \bar{X}_u \delta d \tag{7}$$

where

V_{xf} desired longitudinal speed relative to the station-keeping point at
the threshold, ft/sec

D_f selected threshold range with respect to the station-keeping point, ft

Performing the indicated integrations produces the following relationship between longitudinal speed and range

$$d = -[v_x - V_{xf} - V'_w \ln\left(\frac{v_x + V'_w}{V_{xf} + V'_w}\right)]/\bar{X}_u + D_f \tag{8}$$

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This equation is the desired generalization of equation (1). The reconfiguration range, d_r, is defined as the range at which the inequality

$$d \leq -[v_x - V_{xf} - V'_w \ln \left(\frac{v_x + V'_w}{V_{xf} + V'_w} \right)]/\bar{X}_u + D_f \qquad (9)$$

is first satisfied.

It has been found empirically, using an unpiloted simulation, that the deviation of pitch attitude from the nominal value of 6.5° is minimized for winds up to 40 knots and reconfigured nozzle angles above 75° if $\bar{X}_u$ is varied with Θ_{jf} and V_w according to the equation

$$\bar{X}_u = \bar{X}_{u_0} + \bar{X}'_u[V_w + \frac{g \cos (\theta_n + \Theta_{jf})}{K_{\theta_j}}] \qquad (10)$$

where

$\bar{X}_{u_0}$	baseline estimate of the slope of the range vs. airspeed line, 1/sec
$\bar{X}'_u$	rate of change of the slope of the range vs. airspeed line with the effective wind, 1/ft
K_{θ_j}	constant parameter, 1/sec

Equation (10) was used in the simulation, but further informal piloted tests indicated that the improvements promised by it were undetectable to the pilots.

The problem with equation (9) is that it gives excessively large values for the reconfiguration range, d_r, for tailwinds; in fact d_r becomes infinite when $V'_w = -V_{xf}$. The nature of the problem can be seen from the simple example where $V_{xf} = 0$, $V_w = -1\text{ft/sec}$ and $\theta_n + \Theta_{jf} = 90°$. Here, since the gross thrust vector is pointing in the vertical direction, the aircraft must end its deceleration moving forward at the tailwind speed of 1 ft/sec and will never come to a hover (i.e., d_r is infinite). The solution to this problem is to set a lower bound of zero on the effective wind speed, V'_w. With $V'_w = 0$, equation (6) shows that

$$\cos(\theta_n + \Theta_{jf}) = -V_w \bar{X}_u/g \qquad (11)$$

and since the right hand side of equation (11) is small, $\theta_n + \Theta_{jf}$ can be expressed in the form

$$\theta_n + \Theta_{jf} = 90° + \Delta(\theta_n + \Theta_{jf}) \qquad (12)$$

where $\Delta(\theta_n + \Theta_{jf})$ is a small angle. It follows from equations (11) and (12) that

$$\Delta(\theta_n + \Theta_{jf}) \approx V_w \bar{X}_u/g \qquad (13)$$

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For the YAV-8B (table 1), equation (13) shows that

$$\Delta(\theta_n + \Theta_{jf}) \approx 1° \text{ per 10 knots of tailwind}$$

It follows that, for the YAV-8B, the pilot can elect to either use the standard hover stop ($\Theta_{jf} = 83.5°$), in which case the guidance law will indicate a pitch angle that is on the average 1° per 10 knots of tailwind higher than the nominal, or he/she can preselect the nozzle angle 1° per 10 knots of tailwind higher than the hover stop, in which case the guidance law will guide the pilot to fly the aircraft at the nominal 6.5° approach pitch angle.

Table 1. Exponential-deceleration speed guidance law constants

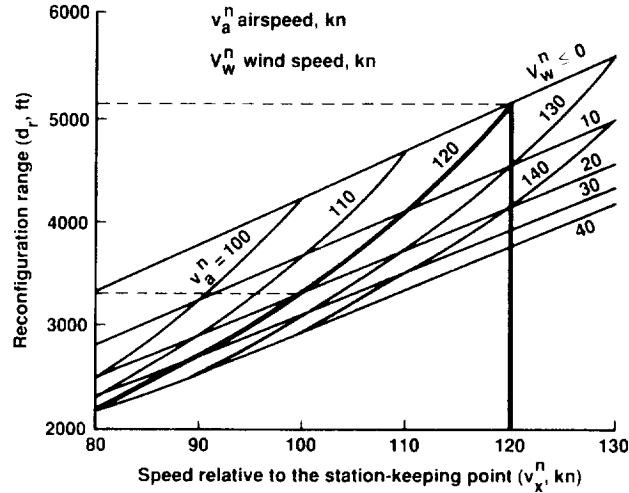| Parameter	Value	Units	Parameter	Value	Units
D_f	200.0	ft	$\bar{X}_{u_0}$	−0.037	1/sec
K_{ax}	0.632	deg sec^2/ft	V_{xf}	20.0	ft/sec
K_{θ_j}	2.0	1/sec	ΔT	2.0	sec
θ_n	6.5	deg	ΔV	3.0	ft/sec
$\bar{X}'_u$	0.00015	1/ft	Θ_{jf}	83.5	deg

Figure 2. Variation of reconfiguration speed with range.

The variation of the reconfiguration range, d_r, with speed calculated from equation (9), is shown in figure 2 using parameter values appropriate to the YAV-8B (table 1). This graph clearly shows the large effect of winds. For example, if the airspeed at reconfiguration is 120 knots, then the appropriate range for reconfiguration in calm air is 5140 ft, whereas in a 20-knot wind it is 3310 ft and in a 40-knot wind it is only 2150 ft, less than half the value in calm air.

It is of interest to compare the reconfiguration range, d_r, given by equation (9), with that given by the procedure used in reference 1. The approach adopted in reference 1 accounts for winds by assuming that the deceleration equation for the zero wind case (e.g.,

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equation (1)) holds in an axes system moving with the wind. For example, equation (1) would be generalized to become

$$d = -(v_x - V_w)/\bar{X}_u \tag{14}$$

which, allowing for a nonzero threshold range and speed becomes

$$d = -(v_x - V_{xf} - V_w)/\bar{X}_u + D_f$$

The reconfiguration range, d_r, is then the range for which the inequality

$$d \leq -(v_x - V_{xf} - V_w)/\bar{X}_u + D_f \tag{15}$$

is first satisfied.

It should be recognized that equation (15), which is based on a kinematical transformation, is only approximate. Equation (9), on the other hand, is based on an integration of the equation of motion (eq. (4)) and is exact. It is clear that the approximation in equation (15) is equivalent to assuming that the logarithm in equation (9) is unity. The effect of this assumption is to overestimate the effect of winds on the reconfiguration range. For example in a 40-knot headwind, such as can occur when landing on a ship, the reduction of the reconfiguration range from the zero wind value given by equation (15) is about 1850 ft, whereas the corresponding number from equation (9) is 1300 ft.

The merit of equation (15) is that it does not contain transcendental functions. This feature may be of benefit for some types of onboard computers. This feature can still be retained and the equation made more accurate by multiplying the wind speed by an empirically determined constant factor, as follows,

$$d \leq -(v_x - V_{xf} - 0.7V_w')/\bar{X}_u + D_f \tag{16}$$

where the effective wind speed, V_w', has been used to allow for cases in which $\theta_n + \Theta_{jf} \neq 90°$.

In the 40-knot headwind case used earlier, equation (16) reduces the error in equation (15) from 550 ft to close to zero. Although equation (9) was used in the simulation, equation (16) would have worked equally well and is recommended because of its simplicity.

EXPONENTIAL-DECELERATION SPEED GUIDANCE LAW

If the aircraft is in the steady state descending along the glideslope at a speed v_x, then equation (9) can be used to determine the range d_r at which the pilot must move the nozzle to the hover position, Θ_{jf}. To allow for the pilot-reaction time, the signal to

move the nozzle to the hover position is given to the pilot at a range d_p that is ΔT seconds earlier than the value given by equation (9), thus,

$$d_p = d_r + v_x \Delta T \tag{17}$$

Following the aircraft's reconfiguration, it is required to define a deceleration law that can be used as the reference from which a guidance signal can be generated. The approach adopted in reference 1 was to define a suitable speed schedule as a function of range (eq. (14), for example) and then using the difference between this reference speed and the aircraft's groundspeed as the basis for the guidance. The concept of basing a guidance scheme on a predefined speed schedule overconstrains the deceleration task, and therefore makes the pilot workload higher than necessary, probably considerably higher than when performing the task visually. When performing the visual task, the pilot makes no attempt to follow any preconceived speed schedule. As expressed in reference 4, based on a statement made by one of the pilots during a previous simulation, "All that matters to the pilot is that adequate safety margins be maintained and that the speed error at the end of transition be sufficiently low to permit capture of the initial station-keeping point without making large thrust vector angle or pitch angle changes." It is a reasonable supposition that during visual decelerations the pilot judges a desired deceleration based on the range and closure rate to objects close to the station-keeping point. An approach similar to the visual deceleration technique is suggested in reference 5. Here, it is proposed to provide the pilot with a continuous indication of the level of constant deceleration required to reach the initial station-keeping point with zero speed. The pilot is required to fly the aircraft so that the actual deceleration is equal to the desired one. With such a guidance technique there is no explicit schedule that defines the velocity as a function of the range; instead there is a reference deceleration that is a function of both speed and range. Furthermore, this reference deceleration varies slowly to compensate for pilot tracking errors, thus helping to reduce pilot workload. The reference deceleration technique has been used for nominally constant deceleration transitions with considerable success (ref. 6) and forms the basis of the constant-deceleration speed guidance law to be described later. The major task for the pitch modulated deceleration scheme is defining a reference deceleration that takes account of the exponential "bleed-off" of aircraft speed following either a pitch angle or engine-nozzle angle change. This is easily deduced from equation (1). Differentiating equation (1) with respect to time gives

$$\dot{v}_x = \bar{X}_u v_x \tag{18}$$

and substituting $-v_x/d$ for $\bar{X}_u$ in this equation gives

$$\dot{v}_x = \frac{-v_x^2}{d} \tag{19}$$

The value of $\dot{v}_x$ calculated from equation (19) then provides the appropriate exponential reference deceleration, $\dot{v}_{xr}$, thus

$$\dot{v}_{xr} = \frac{-v_x^2}{d} \tag{20}$$

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It should be noted that the corresponding reference deceleration for the constant-deceleration law is

$$\dot{v}_{xr} = \frac{-v_x^2}{2d} \tag{21}$$

The similarity between the laws for the two types of deceleration (eqs. (20) and (21)) is striking.

Since a given final speed, V_f, is desired, it is necessary to append to equation (19) the condition

$$\dot{v}_{xr} = 0 \qquad \text{if } v_x \leq V_f + \Delta V \tag{22}$$

The quantity ΔV (typically 3 ft/sec) is needed to compensate for the speed loss due to the lag between the commanded and achieved zero acceleration at the end of transition. It will be noted that the condition given by equation (22) also avoids the need to deal with the singularity that occurs in equation (20) when $d = 0$.

It should be noted here that only the range at which the pilot is first requested to change the engine-nozzle angle is determined by the nominal nozzle position for hover, Θ_{jf}. The deceleration guidance law is activated when the nozzle angle exceeds some preset value (currently 75°). There is nothing in the formulation of the guidance law that prevents the pilot from changing the nozzle angle a few degrees during the deceleration to provide a more desirable pitch angle in hover. The guidance law simply asks for a particular deceleration, which can be met by changing pitch angle, nozzle angle or a combination of both.

CONSTANT-DECELERATION SPEED GUIDANCE LAW

A different approach to the problem of devising a speed guidance law employs a control technique that differs fundamentally from that used currently and on which the previously derived speed-guidance law depends. In this control technique, the pitch angle is maintained constant at the nominal touchdown value and the deceleration is modulated solely by changes of engine-nozzle angle, which is the reverse of the currently used control technique. This reverse control technique is clearly unsuited to the current Harrier control system, since it would require the pilot to move his hand from the throttle to the nozzle lever continually during the deceleration. However, if the control system were modified so that control of thrust and engine-nozzle angle were integrated into a single control inceptor, the reverse technique could become viable. A method of integration has been simulated (refs. 3-5) in which the pilot could command the engine-nozzle angle to change at a fixed rate (typically 3°/sec), in either direction, by pressing a switch located on the top of the throttle. The system was simulated in conjunction with a constant-deceleration speed guidance law (ref. 2). Briefly, this law assumes a two-step deceleration in which the deceleration during each step is nominally constant. The initial deceleration level is selected by the pilot and depends on how aggressively he wishes to perform the approach. The final deceleration level is always the same (typically 1.5 ft/sec²), is independent of the

initial deceleration level, and is always held for approximately 35 seconds. The two-step deceleration forces the kinematics of the final approach to be always the same and avoids aircraft handling problems that could ensue from the high rates of closure at the end of the approach that can occur with a single-step deceleration. This speed guidance law, along with the simple integrated power management controls indicated above, is included for comparison in the subject simulation evaluation.

HEAD-UP DISPLAY FORMAT AND DRIVE LAWS

The approach and hover modes of the HUD format used in the simulation are shown in figure 3. In previous applications of this HUD (ref. 6), longitudinal guidance was provided by the two-step constant-deceleration law described earlier. The longitudinal guidance symbol on the HUD format is identified in figure 3. This symbol is called an "acceleration-error ribbon" since its length is proportional to the difference between the longitudinal acceleration of the aircraft and the reference acceleration (ref. 2). For the constant-deceleration speed guidance law, the acceleration-error ribbon appears on the HUD when the range is such that the aircraft will decelerate to a hover at the station-keeping point if the deceleration levels were precisely the pilot selected initial one and the fixed final one. The pilot's task is to maintain the flightpath symbol coincident with the ghost-aircraft symbol using power and lateral stick, while changing the engine nozzle angle so as to null the acceleration ribbon. This same ribbon is used to indicate information from the exponential-deceleration speed guidance law derived here. Again, the length of the ribbon, f_{ae}, (see fig. 3) is made proportional to the acceleration error, thus

$$f_{ae} = K_{ax}(\dot{v}_x - \dot{v}_{xr}) \tag{23}$$

where K_{ax} is a fixed gain. The pilot is alerted to move the nozzle to the final (hover) position by the sudden appearance of the ribbon at a length of $+5°$, measured on the HUD pitch scale. After the nozzle is moved beyond $75°$, the ribbon commences to display the acceleration error.

For either type of speed-guidance law, when the speed relative to the station-keeping point is less than 35 ft/sec, a "velocity-error line" appears on the HUD (fig. 3(a)). The length of this line is proportional to the speed relative to the station-keeping point. When the distance from the station-keeping point is less than 280 ft, the "longitudinal position indicator" (fig. 3(a)) appears and traverses down the HUD. The longitudinal-position indicator identifies the position of the station-keeping point relative to the aircraft. At a range of between 50 ft and 100 ft the pilot switches to the HUD hover mode (fig. 3(b)) and proceeds to use the associated hover guidance (ref. 2) to acquire the station-keeping point. The HUD displayed guidance technique described above is slightly different from that used in previous simulations using the two-step constant-deceleration speed guidance law in that, previously, the acceleration error ribbon disappeared simultaneously with the appearance of the speed-error line. Maintaining the acceleration error ribbon all the way
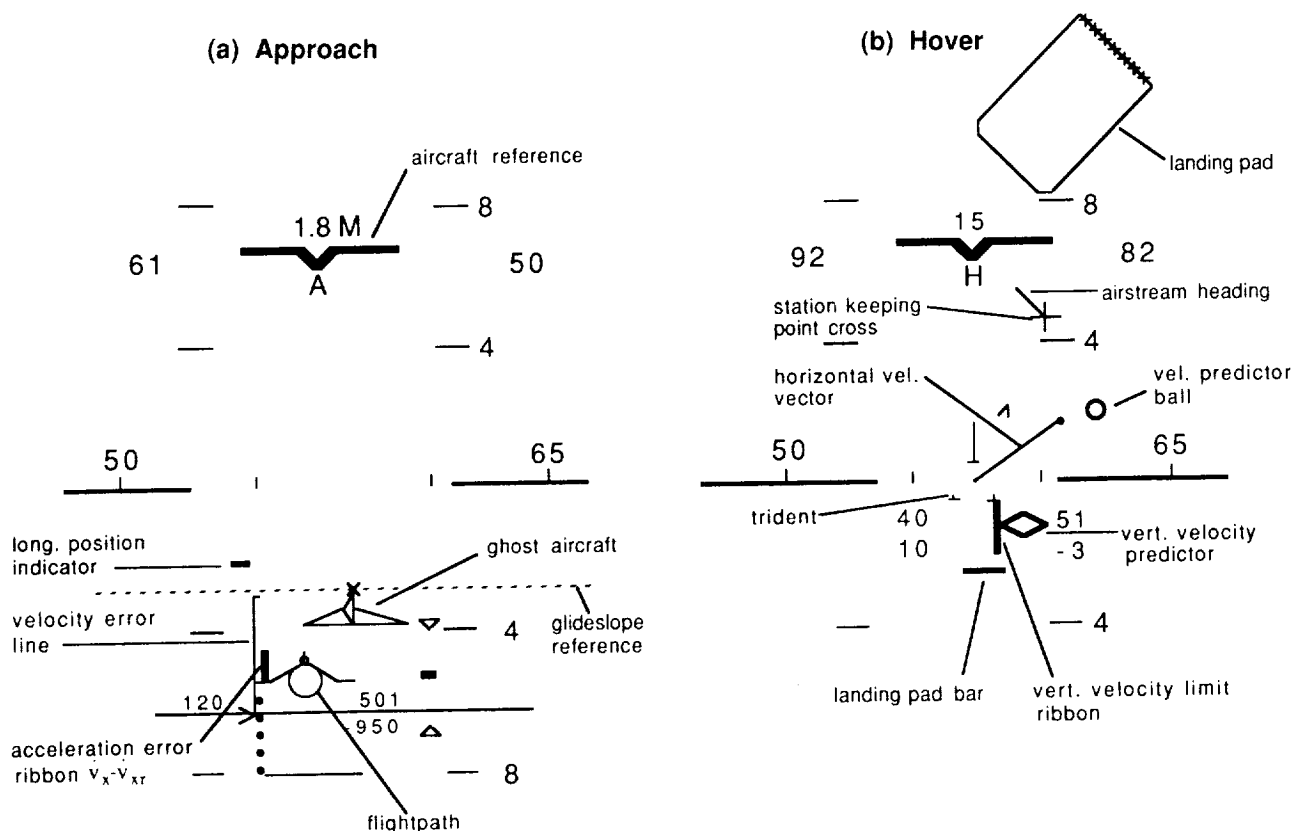
11

(a) Approach

(b) Hover

aircraft reference

— — 8
1.8 M
61   A   50
—   — 4

50   65

long. position indicator ——— ■

ghost aircraft

velocity error line ——

120 ▷ ● 50 1
950 △

acceleration error ribbon v_x-v_{xr} — ● — — 8

glideslope reference — 4 ▽

flightpath

landing pad

— 15 — 8
92   H   82

airstream heading

station keeping point cross

horizontal vel. vector

vel. predictor ball ◯

50   65

trident 40
10

51
- 3

vert. velocity predictor

— / — 4

landing pad bar   vert. velocity limit ribbon

Figure 3. Approach and hover display formats.

to the changeover in HUD mode was found to help when using either speed guidance law, since it prevents any possibility of there being a period at the end of the approach where no speed guidance is provided to the pilot.

CONTROL SYSTEM CONFIGURATIONS

Three control system configurations were used to assess the effect of the degree of control augmentation on the speed-guidance law evaluation. The simplest control system used was the YAV-8B Harrier rate damped SAS. The other two, more advanced control systems, provided attitude stabilization in the form of either rate command with attitude hold (RCAH) or attitude command (AC). The mechanization of the RCAH and AC systems employed 3° of stabilator series actuator authority, which is that of the AV-8B Harrier II. Listed in table 2 are further details of the types of augmentation and stabilization provided by the three control system configurations:

The RCAH and AC advanced control modes were implemented using the state-rate-feedback implicit-model-following control algorithm discussed in reference 7. This control mode implementation achieves excellent model following over a wide range of model dynamics by utilizing high gain feedback of the aircraft's state and state rate. The dynamics of the RCAH and AC control system models are listed below and generally conform to

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Table 2. Control augmentation and stabilization alternatives

Rate damping SAS

Pitch—rate damping (standard YAV-8B)

Roll—rate damping (standard YAV-8B)

Yaw—rate damping with roll-to-yaw interconnect for improved turn coordination (standard YAV-8B)

Nozzle—capability for fixed-rate trim through a switch located atop the throttle lever (not standard YAV-8B)

Rate command attitude hold (RCAH)

Pitch—RCAH through the longitudinal stick

Roll—RCAH through the lateral stick

Yaw (approach)—sideslip command through the rudder pedals with automatic turn coordination

Yaw (hover)—rate command through the rudder pedals

Nozzle—capability for fixed-rate trim through a switch located atop the throttle lever

Attitude command (AC)

Pitch—AC through the longitudinal stick

Roll—RCAH through the lateral stick

Yaw (approach)—sideslip command through the rudder pedals with automatic turn coordination

Yaw (hover)—rate command through the rudder pedals

Nozzle—capability for fixed-rate trim through switch located atop the throttle lever

those found to be optimum in previous studies at Ames (refs. 3–8).

$$\text{Pitch}: \quad \frac{\dot{\theta}}{\dot{\theta}_c} = \frac{4}{s^2 + 4s + 4} \quad , \quad \frac{\theta}{\theta_c} = \frac{4}{s^2 + 4s + 4}$$

$$\text{Roll}: \quad \frac{\dot{\phi}}{\dot{\phi}_c} = \frac{4}{s^2 + 4s + 4}$$

$$\text{Yaw(approach)}: \quad \frac{\beta}{\beta_c} = \frac{4}{s + 4}$$

$$\text{Yaw(hover)}: \quad \frac{\dot{\psi}}{\dot{\psi}_c} = \frac{4}{s + 4}$$

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SIMULATION DESCRIPTION

Facility

The simulation evaluations were conducted using the Ch.06 fixed-base cab (fig. 4) at Ames Research Center. The simulator cab configuration consisted of an AV-8A Harrier power-management quadrant, standard stick and rudder pedals, a simple instrument panel layout and an advanced visual system. The Ch.06 simulator has a single-window wide-field-of-view computer generated image (General Electric CT5A). A conformal HUD is optically superimposed on the CT5A generated image. The HUD symbology is generated with a Sperry Programmable Symbol Generator with an ARINC interface to provide compatibility with the Ch.06 visual display equipment.

Aircraft Description

The YAV-8B Harrier shown in figure 5 is a single seat, high performance, transonic, light attack V/STOL aircraft that served as the prototype AV-8B Harrier II. The aircraft is characterized by a shoulder-mounted supercritical swept wing and a swept stabilator, both with marked anhedral; a single vertical fin and rudder; under-fuselage lift improvement devices; an improved inlet design with a double row of suck-in doors; and four vectorable engine exhaust nozzles, two on each side of the fuselage.

A single Rolls Royce Pegasus turbofan engine provides lift thrust for takeoff and landing, cruise thrust for conventional wing borne flight, deflected thrust for V/STOL and in-flight maneuvering, and compressor bleed air for the aircraft's reaction control system (RCS). The nozzle system can direct the engine thrust from fully aft, through vertical, to slightly forward of vertical.

Reaction control system (RCS) jets are used in hovering flight and conventional aerodynamic surfaces in wing borne flight, with both systems contributing during transition. Hydraulically powered control surface actuators are integrated with an electronically controlled, limited authority SAS. Longitudinal control is achieved by use of downward blowing front and rear fuselage RCS jets and an all-moveable stabilator. Lateral control is achieved by use of RCS jets thrusting up or down at the wing tips and outboard ailerons. Directional control is achieved by use of a sideways blowing (left or right) RCS jet located at the fuselage tail and by a conventional, unpowered rudder.
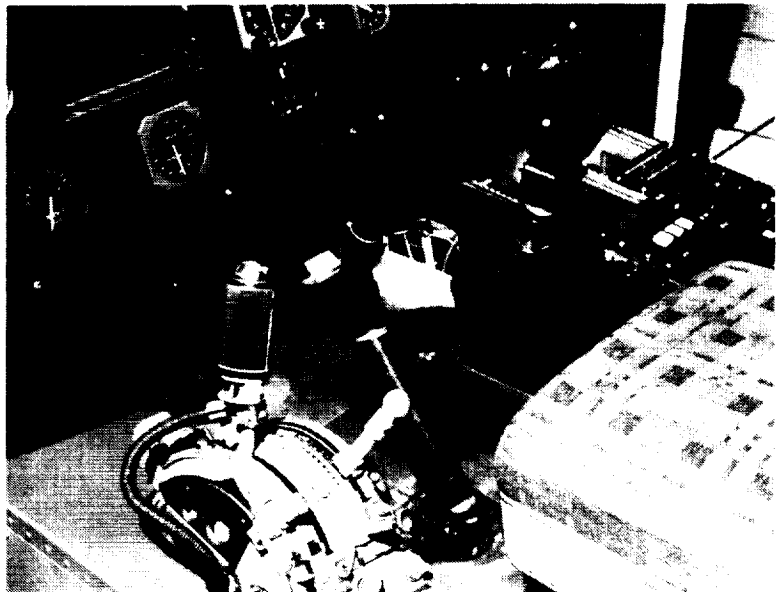
Mathematical Model

The YAV-8B mathematical model is derived from a YAV-8B model developed from wind tunnel and engine test data (ref. 9) by McDonnell Douglas Corporation (MDC), and an AV-8B model developed by parameter identification techniques from flight test data (ref. 10) by Systems Control Technology (SCT). An extensive set of one-, two-, and three-dimensional curves is used for the YAV-8B aerodynamic and engine performance characteristics in the MDC formulation, whereas a relatively simple algebraic formulation

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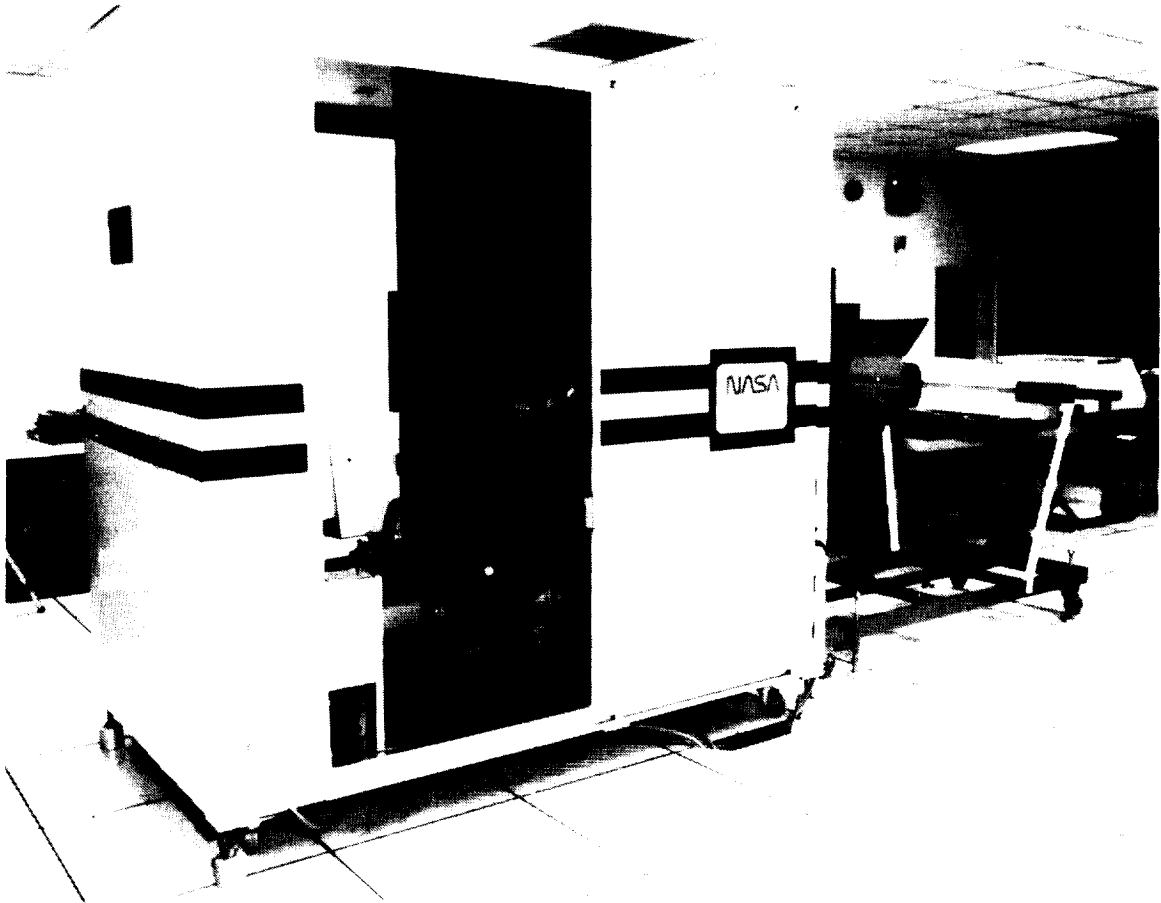
(a) Overall arrangement of cab and visual system
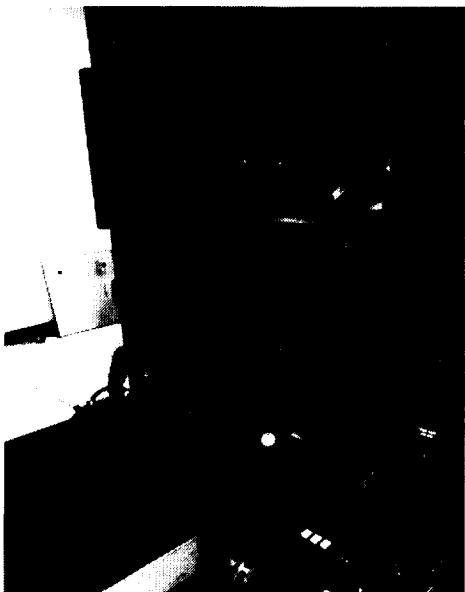
(b) General cockpit arrangement

(c) Harrier power management console

Figure 4. Fixed-base simulator.

30.33 ft

11.25 ft

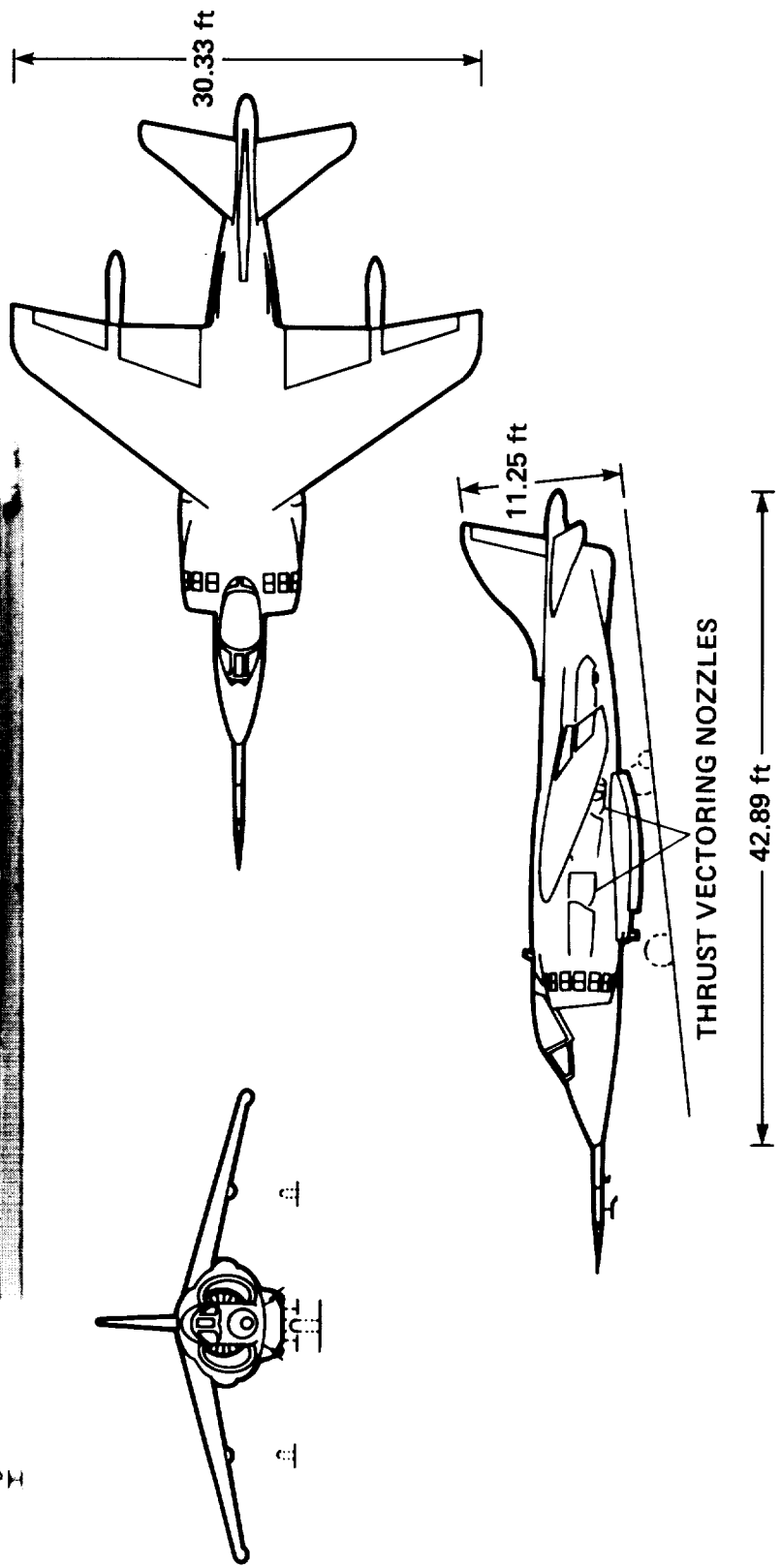THRUST VECTORING NOZZLES

42.89 ft

Figure 5. YAV-8B Harrier.

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of the AV-8B's aerodynamics is used in the SCT mathematical model. Although the modeling techniques used to represent the aerodynamic forces and moments in the two models differ considerably, simulations at Ames indicate that the flying qualities in the low speed flight regime of interest for the speed-guidance law evaluations are similar. Therefore, to minimize the computer cycle time, the faster algebraic formulation of the SCT AV-8B models was substituted for the computationally intensive table look-ups of the YAV-8B model. After the addition of the code for the guidance, control and display functions described earlier, the Xerox Sigma computer frame time was 74 msec.

Simulated Task

The task used to evaluate the speed-guidance law involved flying a $-3°$ flightpath angle, γ, in a straight, decelerating approach in IFR conditions (one-quarter n. mi. RVR and 100 ft ceiling) to a STOL runway, ending in a stabilized hover 50 ft above a desired touchdown point. The touchdown point was marked on the runway and by either the "longitudinal-position indicator" or the "station-keeping-point cross" on the HUD (fig. 3). The task was regarded as complete when the aircraft was within 5 ft of the station-keeping-point cross. Initial conditions for the aircraft were $\gamma = -3°$, $v_a^n = 120$ knots, $\theta_j = 41.5°$, $d = 1.5$ n. mi. In addition to the visibility conditions, the tests were conducted in three simulated environmental conditions; namely calm air, 20 knots with 3 ft/sec rms turbulence and 40-knot winds with 6 ft/sec rms turbulence. The overall task takes place in three consecutive phases. Phase 1 is a low precision, constant speed initial approach that simply requires the pilot to follow the ghost aircraft using small changes of pitch from a nominal approach value. Phase 2 is a moderate-precision part of the deceleration, which requires the ghost aircraft to be followed using power while, for the exponential-deceleration speed guidance, moving the nozzles to the hover stop and zeroing the speed guidance ribbon with pitch attitude changes or, for the constant-deceleration speed guidance, zeroing the speed guidance ribbon using the nozzle switch while maintaining constant pitch attitude. Phase 3 is a high precision part of the deceleration from semi-jet-borne to jet-borne flight requiring closure to the station-keeping point and the establishment of a stable hover close to the station-keeping point.

Pilot ratings, using the Cooper-Harper Handling Qualities Rating Scale (ref. 11), were used to measure the ease of performing the task for all combinations of the two deceleration guidance schemes, the three types of control systems, and the three environmental conditions.

PILOT EXPERIENCE

Three pilots participated in the simulation. Two were test pilots with NASA Ames Research Center and the third was employed by SYRE Corp. One of the NASA pilots, previously a Marine Corps test pilot, had 2,700 hr, largely in military combat aircraft, including 1,000 hr in Harriers and, in particular, 300 hr in the YAV-8B. The other NASA

pilot had 10,000 hr in various civil and military aircraft types, including 1,000 hr in a variety of STOL aircraft, VTOL aircraft and helicopters and, in particular, 100 hr in Harriers. The SYRE Corp. pilot, a former NASA test pilot, had 10,000 hr in various civil and military aircraft types, including 2,000 hr in a wide variety of STOL aircraft, VTOL aircraft and helicopters including 150 hr in Harriers and, in particular, 75 hr in the YAV-8B.

All three pilots had experience with the simulation facilities at Ames Research Center and were well qualified to predict the results that might be expected in real flight.

SIMULATION VALIDATION

The simulator had several notable deficiencies, all of which were certain to affect the simulation fidelity. These deficiencies were

1. The simulator was fixed base (no motion cues).

2. The visual attachment had a single forward looking cathode-ray tube with only a 48° wide by 28° high field of view.

3. The stick and pedal force gradients were only about one half of those of the YAV-8B. The pedals had very high Coulomb friction and therefore poor self-centering.

4. No engine noise or other aural cues were provided.

5. The simulation required a relatively high computer cycle time (74 msec) and correspondingly large visual display lags.

Clearly, the simulator environment differed considerably from that of the real aircraft requiring the pilots to judiciously extrapolate the simulator experience to flight. Simulator deficiences are more serious in those situations requiring the greatest pilot compensation, which in this simulation occurred when performing tests with the basic YAV-8B. Since the pilots had all flown the basic YAV-8B, the validation tests naturally centered on flying the simulation of the YAV-8B with SAS visually along the approach path, noting attitude response to stick and pedal inputs and heave response to throttle inputs.

The most important differences perceived by the pilots were that the pitch, roll and heave damping of the simulated aircraft were less, and in the case of pitch and roll considerably less, than the real aircraft. The most likely reasons for these effects are the very high computer cycle time plus the visual system delays. The reduced pitch and roll damping was evident at all airspeeds on the approach (less than 130 knots), while the reduced heave damping was evident at low speeds (less than 40 knots). Apparent damping reductions of this type, although less severe, have been noted in previous simulations of the YAV-8B using this mathematical model.

To compensate for the perceived lack of pitch and roll damping, the pitch and roll SAS feedback gains, stick gearing and SAS servo authorities were all increased by the same

factor. This procedure increases the attitude rate damping while maintaining roughly constant the steady state relationship between the stick input, the pitch and roll rates and the pitch and roll rates at SAS servo saturation. To compensate for the perceived lack of heave damping, a simple heave damper using vertical velocity feedback was added to the engine speed control. Tests were performed with various levels of damping augmentation until the pilots were satisfied that the simulation was adequately representative of the real aircraft.

It was found that the factor used in the pitch and roll control control channels had to be set to a value of three before the pilots were satisfied with the perceived level of damping. This is a surprisingly high value, but the pilots were in agreement that the pitch and roll characteristics then appeared to be qualitatively similar to the real aircraft. It was also found that the heave-damper gain had to be set to provide a damping equivalent to a Z_w of -0.14 sec^{-1} in order for the perceived heave damping to match the real aircraft. Since the measured Z_w of the real aircraft is about -0.02 sec^{-1}, the added damping is, again, surprisingly large.

What should now be readily apparent is that the simulation exercise by its very nature could supply only a crude handling qualities assessment of the two decelerating techniques under investigation. The pilots fully recognized the limitations of the simulation and the necessarily tentative nature of the results.

RESULTS

The Cooper-Harper Handling Qualities Ratings (HQR) obtained during the simulation are shown in figure 6. With the basic YAV-8B control system, the handling qualities were only acceptable (level 2) independent of the type of speed guidance. The average HQRs for the exponential-deceleration guidance varied from slightly less than 4 in calm air to 5 in 40 knots of wind and 6 ft/sec turbulence. The constant-deceleration guidance was rated worse than the exponential-deceleration guidance by an average HQR of about 1. With one minor exception (attitude-command in 40 knots of wind and 6 ft/sec turbulence), the HQRs obtained using either the rate command, attitude hold or attitude command control systems were satisfactory (level 1) independent of the type of deceleration guidance. The type of speed guidance had only a minor effect on the pilot ratings, the average HQRs varying from 1.5 in calm conditions to between 3.5 and 4 in 40 knots of wind and 6 ft/sec turbulence. The data suggest that when using the attitude command control system, the constant-deceleration speed guidance law may become progressively superior to the exponential-deceleration speed guidance law as wind and turbulence increase, attaining an average HQR advantage of about 0.5 in the most extreme environmental conditions.

The variation of longitudinal acceleration, groundspeed, nozzle angle, pitch angle and altitude error during typical landing approaches is shown in figures 7 through 12. These figures show the influences on these parameters of both the environmental conditions and the type of speed guidance law when using the basic YAV-8B attitude SAS (figs. 7 and 8),
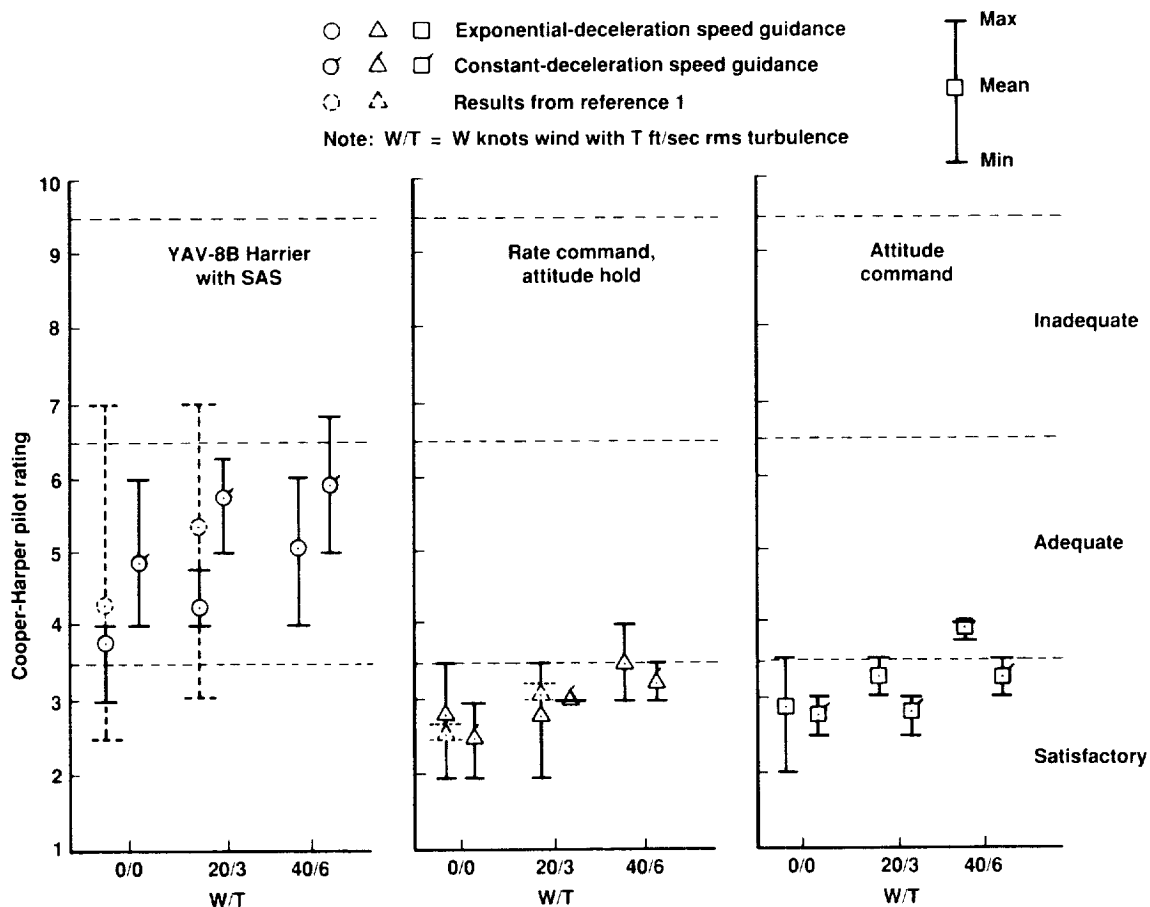
Figure 6. Cooper-Harper handling qualities ratings.

the rate-command-attitude-hold control system (figs. 9 and 10) and the attitude-command control system (figs. 11 and 12). Shown in figures 7 through 12 are the times at the start of the deceleration (I), the arrival at the 200-ft range threshold (II) and hover at the station-keeping point (III).

To aid in understanding the handling qualities ratings, a compilation of edited pilot comments, recorded during the simulation, is given below. These comments are organized under three major headings corresponding to the three control system tested and two sub-headings corresponding to the two speed guidance laws tested. Comments that appear under the major control system headings apply to both types of speed guidance. It is useful to refer to figures 7 through 12 when reading these pilot comments.

Basic YAV-8B Control System (figs. 7 and 8)

1. Continuous changes of the throttle setting during the deceleration causes continuous pitch excitation, which, in turn, requires constant monitoring and correction. This pitch excitation, which is increased considerably in turbulent conditions, provides an additional high frequency task that significantly increases the workload.

2. The pitch and roll excitation due to turbulence makes the task of tracking the ghost aircraft symbol with the flightpath symbol difficult. The influence on overall pilot workload can be minimized by relaxing the tracking accuracy in the early and middle portions of the approach.

3. In high winds, the initial approach groundspeed is reduced (fig. 2) and the deceleration time is reduced correspondingly. This time compression increases the workload.

4. The combined workload involved in following the three-cue guidance while simultaneously keeping the pitch under control leaves too little time for checking the status information on the HUD.

Constant-Deceleration Speed Guidance Law (fig. 7)

1. This law requires multiple nozzle angle changes, each of which causes an additional pitch disturbance and thereby aggravates the pitch control problem.

2. Since the nozzle angle has to be changed several times, three high frequency tasks have to be performed simultaneously (throttle, nozzle and pitch).

3. Some practice is needed to minimize the number of nozzle angle changes during the deceleration and a conscious effort must be made to zero the acceleration error towards the end of the deceleration. Otherwise the final nozzle angle is not correct for the hover and final nozzle angle corrections occur at a time of already high workload.

4. Not having to take the hand off the throttle at any time during the landing is a distinct advantage of this deceleration technique.

5. A nozzle-angle rate of 15°/sec is preferred. (Tests were performed at various nozzle-angle rates varying from 3°/sec to 20°/sec.)

Exponential-Deceleration Speed Guidance Law (fig. 8)

1. Except in very high headwinds, all of the nozzle angle change and, therefore, all of the associated pitch disturbance takes place early in the approach when the workload due to other activities is low and there is less of a need to follow the guidance with high accuracy. The result is that the overall workload throughout the approach is less than for the constant-deceleration speed guidance law.

2. In high headwinds, there is a need to reduce the nozzle angle below the preset value to which it is set at the start of the deceleration. This reduction is needed to offset the drag in hover when at the desired hover pitch attitude (6°-7°). The required reduction in nozzle angle is small (about 1° per 10 knots of wind). The need to make this nozzle-angle adjustment adds to the workload, but its impact can be minimized by making the adjustment at some intermediate point in the approach, rather than leaving it to the end when the workload is most concentrated.
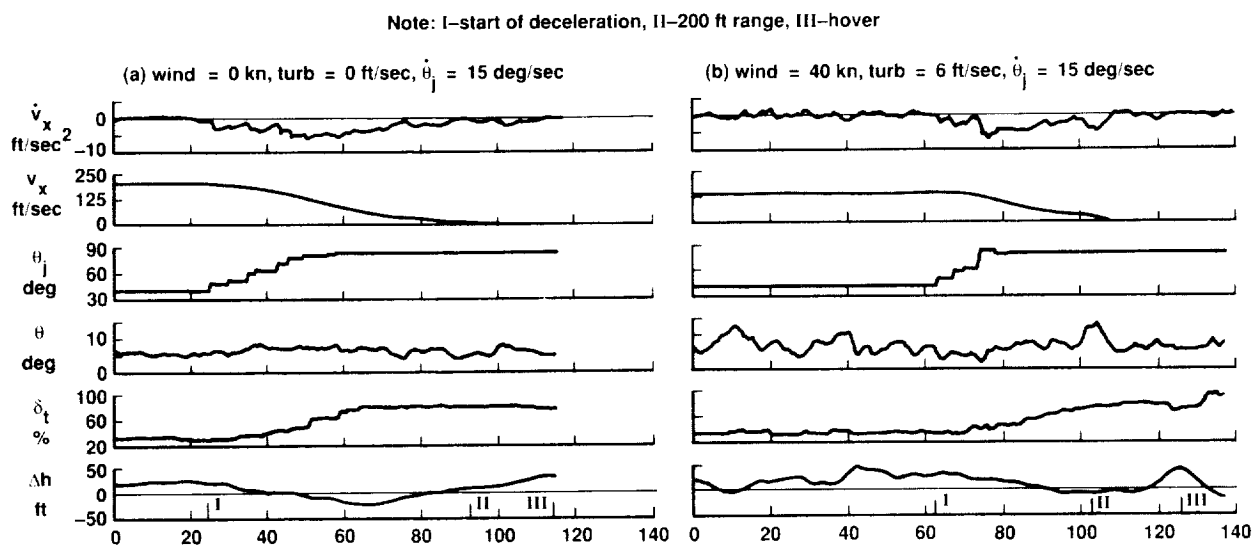
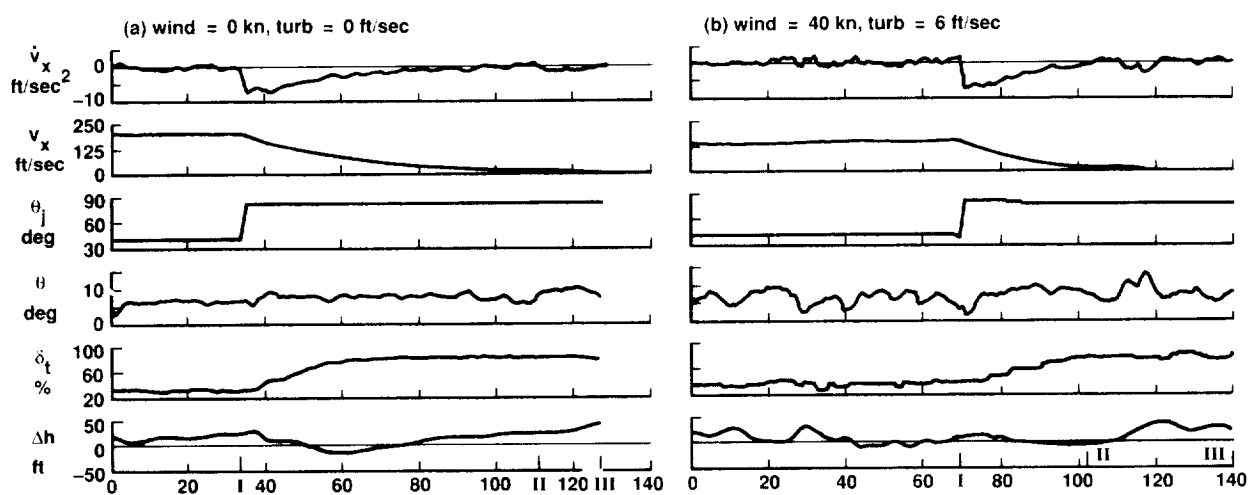Figure 7. Typical approach with constant-deceleration speed guidance law and YAV-8B SAS.

Figure 8. Typical approach with exponential-deceleration speed guidance law and YAV-8B SAS.

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Rate Command, Attitude Hold (RCAH) Control System (figs. 9 and 10)

1. The pitch attitude is much easier to control and no longer represents a constant high frequency task. The attitude hold feature of the control system works well and power changes, nozzle angle changes and turbulence produce only small pitch transients that do not require pilot correction.

2. Turbulence still disturbs the aircraft vertically and laterally, especially early in the approach, although the greatly increased disturbance rejection in both pitch and roll eases considerably the task of tracking the ghost aircraft symbol with the flightpath symbol.

Constant-Deceleration Speed Guidance Law (fig. 9)

1. The low coupling between nozzle angle changes and pitch is beneficial in two respects. A change of nozzle angle does not require a corresponding longitudinal stick input, and the absence of a pitch disturbance minimizes the number of nozzle angle changes required to maintain the deceleration error to an acceptable value.

2. Since the workload is much less than with the basic YAV-8B control system, the deceleration error can be kept to a minimum throughout the approach and the final nozzle angle is close enough to that required for hover that no additional "touch-up" of the nozzle angle is needed.

3. The nozzle-angle rate used is less critical than with the basic YAV-8B control system and rates as low as 3°/sec are acceptable. The reason is that, since the aircraft is much more stable, the scan rate can be reduced and the time available for any particular subtask can be increased, if necessary. The greater time needed to "zero-out" the deceleration error with the reduced rate nozzle is, therefore, less important.

4. The final phase of the approach, using pitch to control the longitudinal velocity, is much easier than with the basic YAV-8B control system.

Exponential-Deceleration Speed Guidance Law (fig. 10)

1. The overall workload differs little from that when flying the constant-deceleration guidance. After the initial large nozzle-angle change, small pitch changes replace nozzle angle changes, and the final phase of the approach is identical for both guidance techniques.

2. In high headwinds, the reduction of nozzle angle and corresponding increase of pitch angle needed to establish the correct pitch angle for landing can be performed easily, but represents a slight increase of workload in mid-approach. Again the improved pitch stability makes this adjustment much easier than with the basic YAV-8B control system.
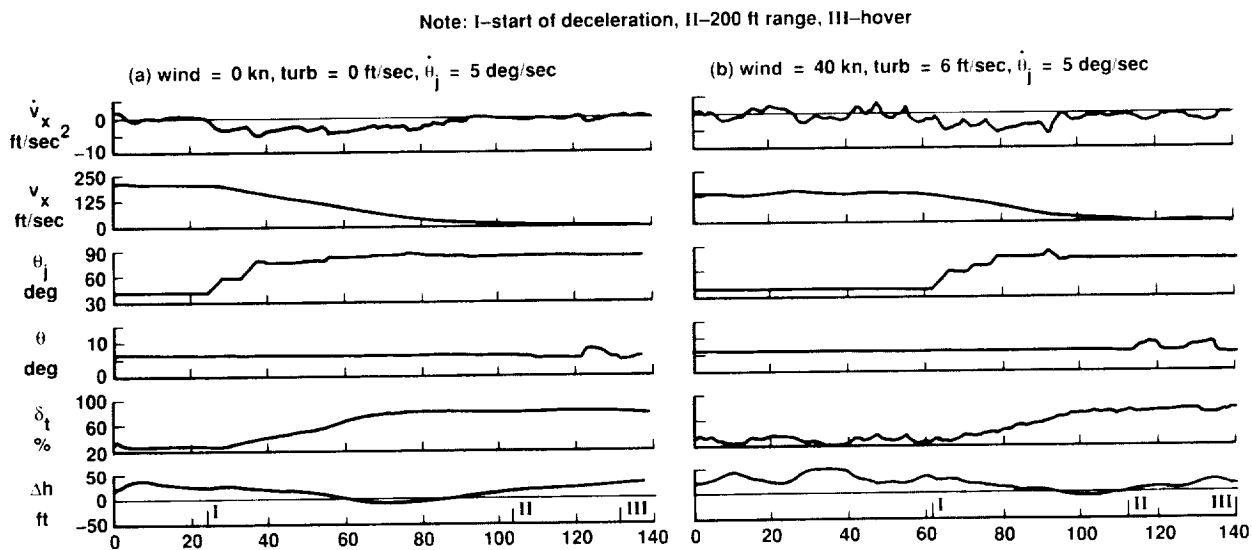
Figure 9. Typical approach with constant-deceleration speed guidance law and rate command altitude hold (RCAH).
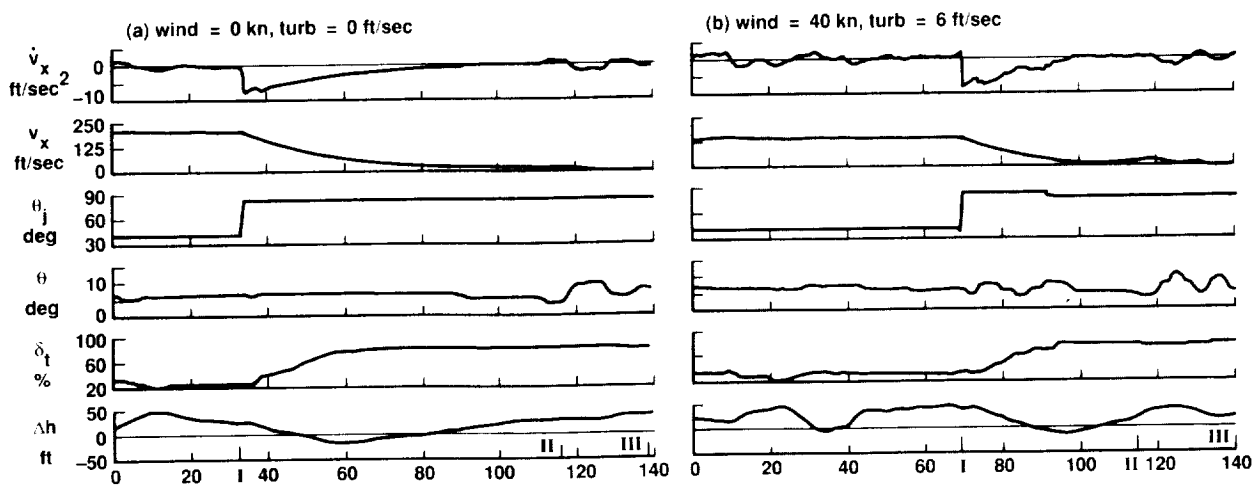

Figure 10. Typical approach with exponential-deceleration speed guidance law and RCAH.

Attitude Command (AC) Control System (figs. 11 and 12)

1. Similar in most respects to the RCAH control system. The attitude stabilization effectively decouples the pitch attitude from the throttle and nozzle and compensates for pitch disturbances due to turbulence.

2. It is somewhat easier to perform the final approach from the threshold to the station-keeping point than with the RCAH control system, and much easier than with the basic YAV-8B control system.

Constant-Deceleration Speed Guidance Law (fig. 11)

The overall workload is almost identical to that when using the RCAH control system. The need to trim out the stick forces during the approach down to the threshold increases the workload slightly, but this is compensated for by the slightly easier task from the threshold to the station-keeping point.

Exponential-Deceleration Speed Guidance Law (fig. 12)

The overall workload is almost identical to that when using the RCAH control system when the winds are sufficiently low that there is no need to reset the nozzle angle and adjust the pitch for landing. In high winds the adjustment of the pitch for landing requires a little more attention and pilot compensation than when using the RCAH control system, largely because of the need to trim out the stick forces.

Comparison with Lebacqz, Radford, and Beilman Results

One aim of the tests reported in reference 1 was to evaluate a considerable number of control and display systems of varying complexity to determine to what extent display quality, in terms of both format design and information content, can compensate for control deficiences. A total of seventeen combinations of controls and displays were tested. However, since only one pilot participated in the evaluation and only two flights were made for each control/display combination, the results show some apparent inconsistencies and it is difficult to obtain an accurate comparison between these results and the more narrowly focused, but more intensively tested, combinations reported here. The difficulty is compounded by the fact that the display formats tested in reference 1 differed markedly from those used in the current tests. In particular, all the displays of reference 1 used compensatory guidance (flight directors), whereas the display used in the current tests used pursuit guidance. Furthermore, for each display used in reference 1 a single format served for both transition and hover, whereas in the current tests separate formats were used. Because of these differences, only a very rough comparison of the two sets of results is possible. In order to make this comparison, two rather sweeping assumptions have been made, namely that the more advanced displays designated AV8-5, AV8-6, ED2-1 and ED2-2 in reference 1 are all comparable and equivalent in information content to the display used in the current tests, and that the results of reference 1 showing environmental influences
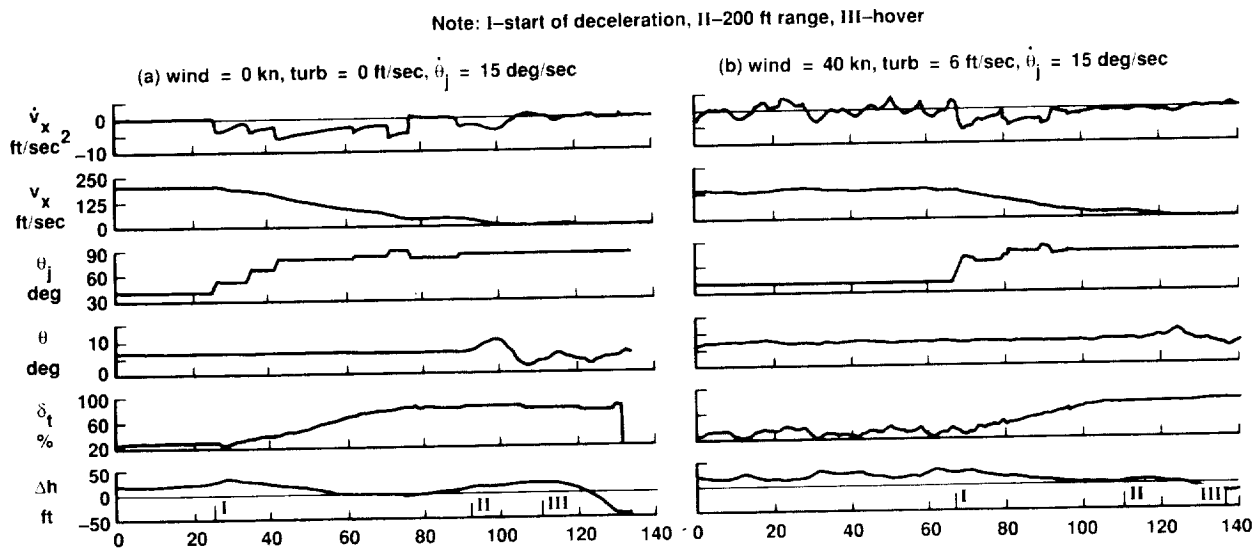
(a) wind = 0 kn, turb = 0 ft/sec, $\dot{\theta}_j$ = 15 deg/sec   (b) wind = 40 kn, turb = 6 ft/sec, $\dot{\theta}_j$ = 15 deg/sec

Figure 11. Typical approach with constant-deceleration speed guidance law and attitude command (AC).

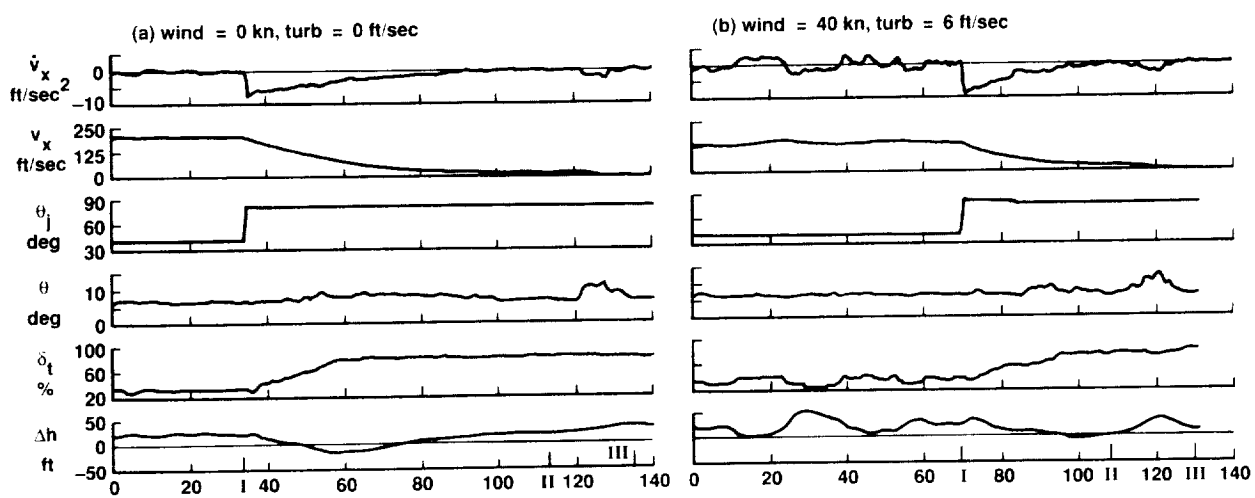(a) wind = 0 kn, turb = 0 ft/sec   (b) wind = 40 kn, turb = 6 ft/sec

Figure 12. Typical approach with exponential-deceleration speed guidance law and AC.

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are equivalent to the 20-knot wind case of the current tests. Using these two assumptions, the HQRs of reference 1 have been consolidated and are shown in figure 6. Only the results for the basic AV-8B control system required the consolidation, since reference 1 tended to concentrate on this control system. There are just two spot HQR values for the RCAH control system. The results for the AC control system given in reference 1 are not compared with the current tests, because the only test performed with a 2 rad/sec system bandwidth suffered from excessive actuator limiting and may not be a representative.

The general conclusion from this comparison (fig. 6) is that, for the particular type of exponential deceleration approach task being considered, both experiments indicate that the handling qualities are level 2 for the aircraft equipped with the standard SAS, and level 1 for the aircraft equipped with a RCAH control system.

Comments

When using the constant-deceleration speed-guidance law, the actual deceleration is far from constant (figs. 7, 9, and 11). The widely varying sawtooth character (fig. 11) of the acceleration is quite understandable bearing in mind the intermittent movement of the engine nozzle by the pilot, and poses no particular problems when the task is performed on a fixed-base simulator. However, such an acceleration characteristic could influence the acceptability of this type of speed guidance in actual flight if the many abrupt changes of deceleration couple inertially with the longitudinal stick and thereby increase the pitch control workload.

It has been stated that some familiarization flying with the constant-deceleration speed guidance law is necessary in order to develop a technique that minimizes the number of nozzle angle changes during the deceleration. It also should be noted that the type of attitude control system used has a significant effect on the number of nozzle angle changes. The effect can be seen clearly by comparison of figures 7 and 11. The much larger number of nozzle angle changes that occur when using the basic YAV-8B control system (fig. 7) is due to the fact that the much larger deviations of pitch using this control system show up on the guidance as acceleration errors which the pilot constantly attempts to remove by changing the nozzle angle.

It can be seen from figures 7 through 12 that the altitude errors vary from about 50 ft above the glidepath to about 20 ft below it. To give some perspective to altitude errors of these magnitudes, the variation of altitude with range for the dataset of figures 7 through 12 is shown in figure 13, along with the conventional 0.25° (one dot) and 0.5° (two dot) glideslope errors. Clearly, the glideslope following is not exceptionally good, but is certainly adequate in that there appears to be no danger of premature ground contact. The altitude errors in the critical region, e.g., below an altitude of 100 ft, could be reduced by progressively "tightening up" the vertical guidance, although this would undoubtedly increase the pilot workload and could have an effect on the pilot handling-qualities ratings.
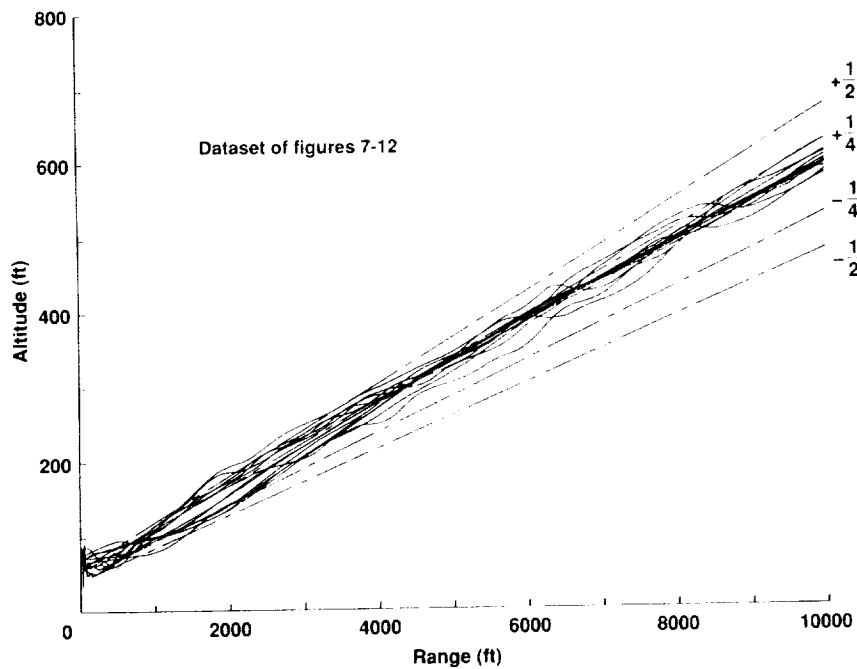
Figure 13. Variation of altitude with range.

CONCLUSIONS

1. The exponential-deceleration speed guidance law was rated generally equal to or better than the constant-deceleration speed guidance law, and since the latter requires an additional piece of control system equipment, the exponential-deceleration speed guidance law is the most cost effective.

2. Handling qualities of the aircraft assumed to be equipped with the standard YAV-8B rate damped attitude SAS were only adequate (level 2) independent of the type of speed guidance used. However, the exponential-deceleration speed guidance law was rated superior to the constant-deceleration speed guidance law by an HQR of about one unit independent of the levels of wind and turbulence. The main reason for this result is that the pilots found it to be less work to counter the single pitch attitude disturbance produced by the single large nozzle angle change made early in the approach, as required for the exponential-deceleration speed guidance law, than to counter the many pitch attitude disturbances produced by the many small nozzle angle changes made throughout the approach, as required for the constant-deceleration speed guidance law.

3. Replacing the attitude control system of the YAV-8B with a high fidelity model-following attitude flight controller increased the accuracy of the approach and reduced the pilot workload, primarily by reducing the pitch attitude disturbance due to engine nozzle changes. With one minor exception, the handling qualities for the approach were rated satisfactory (level 1) independent of the type of speed guidance law, the type of pilot control mode (rate command, attitude hold or attitude-command) and the levels of wind and turbulence. The exception occurred using the attitude-command mode in 40 knots of

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wind and 6 ft/sec of turbulence; even then, handling qualities deficiencies only edged the ratings (HQR = 4) into the adequate (level 2) category.

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16. Abstract

An exponential-deceleration speed guidance law is formulated which mimics the technique currently used by Harrier pilots to perform decelerating approaches to a hover. This guidance law has been tested along with an existing two-step constant-deceleration speed guidance law, using a fixed-base piloted simulator programmed to represent a YAV-8B Harrier. Decelerating approaches to a hover at a predetermined station-keeping point were performed along a straight (–3° glideslope) path in headwinds up to 40 knots and turbulence up to 6 ft/sec. Visibility was fixed at one-quarter n. mi. and 100-ft cloud ceiling. Three Harrier pilots participated in the experiment.

Handling qualities with the aircraft equipped with the standard YAV-8B rate damped attitude stability augmentation system were adequate (level 2) using either speed guidance law. However, the exponential-deceleration speed guidance law was rated superior to the constant-deceleration speed guidance law by a Cooper-Harper Handling-Qualities Rating of about one unit independent of the level of wind and turbulence.

Replacing the attitude control system of the YAV-8B with a high fidelity model-following attitude flight-controller increased the approach accuracy and reduced the pilot workload. With one minor exception, the handling qualities for the approach were rated satisfactory (level 1).

It is concluded that the exponential-deceleration speed guidance law is the most cost effective.

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